SOLAR/2036-79/14

Solar Energy System Performance Evaluation

PAGE JACKSON
ELEMENTARY SCHOOL
Charles Town, West Virginia
November, 1978 through March, 1979

U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $4.50
Microfiche $3.00

SOLAR/2036-79/14
Distribution Category UC-59

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

PAGE JACKSON
ELEMENTARY SCHOOL
CHARLES TOWN, WEST VIRGINIA

NOVEMBER 1978 THROUGH MARCH 1979

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UNDER CONTRACT EG-77-C-01-4049
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NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Page Jackson School project site is designated as SOLAR/2036-79/14. The elements of this designation are explained in the following illustration.

SOLAR/2036-79/14

Prepared for the National Solar Data Program — SOLAR

Demonstration Site — 2036

Year — 79

Report Type Designation — 14

- Demonstration Site Number:

  Each Project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).
  - Solar Energy System Performance Evaluations are designated by the number 14.
  - Solar Project Descriptions are designated by the number 50.
  - Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter

presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the Page Jackson School solar energy system are listed in Section 6, References.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Page Jackson School solar energy system. The analysis covers operation of the system from November 1978 through March 1979. The Page Jackson School solar energy system provides space heating and cooling to an elementary school building located in Charles Town, West Virginia. A more detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgments are extended to those individuals involved in the operation of the Page Jackson School solar energy system. Their insight and cooperation in the resolution of various on-site problems during the reporting period were invaluable.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of the solar energy system installed at the Page Jackson School building located in Charles Town, West Virginia. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

The measurement data were collected [References 7-11]* by the National Solar Data Network (NSDN) [1] for the period November 1978 through March 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

Features of this report include: a system description, a review of actual system performance during the report period, analysis of performance based on evaluation of meteorological load and operational conditions, and an overall discussion of results.

Monthly values of average daily insolation and average outdoor ambient temperature measured at the Page Jackson School site are presented in Table 5.1-1. Also presented in the table are the long-term, average monthly values for these climatic parameters.

The Page Jackson School solar energy system began operation in the late summer of 1978. Various problems prevented the acquisition of complete data from the site in September and October, and the first complete monthly report was issued for November, 1978. Operation of the space

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*Numbers in brackets designate References found in Section 6.

cooling equipment was no longer needed by that time, and has not been used during the five-month period covered in this System Performance Evaluation Report (November 1978 through March 1979). The solar energy system at the site has operated continuously since then with no significant malfunctions or anomolies to prevent monthly reporting.

Weather conditions experienced at the site have been near the long-term average for the overall five-month period but individual months have deviated significantly from the average values. The available solar energy experienced variation from the monthly long-term average during the first three months of analysis. November and January were 17 and 19 percent below the respective averages, while December was 26 percent above the average. The most significant weather conditions which affected the performance of the solar energy system were the lack of available solar energy during January, and the extremely cold temperatures during February.

January was three degrees below normal, resulting in an increased space heating load. The lack of available solar energy caused the demand to be met with auxiliary energy, which then caused the solar fraction for the month to reach a low value of 15 percent. February produced clear but very cold weather with the monthly average being eleven degrees below the long-term average. This produced another large heating demand, and the low ambient temperature reduced the efficiency of the collector array. The result was that during February, although there was almost a normal amount of solar energy available, only fourteen percent of the heating demand could be met by solar energy due to the drop in collector array efficiency. The reduction in collector array efficiency was due to the increased thermal losses from the collectors to the extremely cold atmosphere.

March produced a sharp rebound in performance. The average temperature was 23 degrees warmer than February, and 28 percent more solar energy was available. Collector array efficiency went up to 24 percent, and the heating solar fraction climbed to 66 percent.

Much concern has recently been expressed about the performance of the solar collectors at Page Jackson School. Visual inspection of the collectors during the past winter indicated that several of the absorber plates were buckling with "waves" being observed in the normally flat surfaces. Degradation of the glazing was observed, and several leaks were occurring in the system.

The collector system leaks became worse during the winter months, producing water damage in the classroom area. It was observed that the leaks were more severe when the water in the collectors was cold. Therefore, a procedure was initiated to delay circulation until the collectors were warm, and this reduced the rate of leakage. A portion of the leakage problem has been traced to connections involving slip-on hoses and clamps. Apparently the hoses lose their elasticity after repeated thermal cycling, allowing fluid to leak between the hose and the piping. Traffic on the roof for inspection and repair has evidently started to deteriorate the roof surface.

More recent visual inspection of the collector array resulted in estimates of damaged collectors ranging from 50 to 95 percent of the total array. Some of the collectors with severely warped absorber surfaces were taken apart for internal inspection. The bond between the absorber tubes and the absorber plate was broken and the tubes had separated from the plate. The collectors were manufactured by Pittsburgh Plate Glass (PPG), but they no longer manufacture solar energy collectors. However, as a result of this problem, PPG is testing collectors in an attempt to determine the cause of the degradation.

Detailed analyses were performed by IBM of the Page Jackson School solar collector system in an attempt to determine the extent and cause of the damage. The results indicated that the panels were performing with an efficiency about 40 to 50 percent of the published single panel test efficiency. An installed collector array is expected to perform with less efficiency than a single test panel, but the difference seen here is larger than normally seen. The analyses also did not indicate any continued degradation

of the collector efficiency. Variation of the calculated efficiency curves for the months of October 1978 through April 1979 was within the bounds of scatter in the data, primarily attributable to fluctuations in the atmospheric conditions. Since there is no measured data on the Page Jackson School collector array indicating the actual performance before damage occurred, nor continuously deteriorating performance from which to extrapolate to the pre-damage performance, the fraction of collectors which have been damaged cannot be determined.

With the exception of the collector damage, the Page Jackson School solar energy system does not appear to have any serious problems. Excellent rapport has been maintained with the personnel responsible for the control system, and this has resulted in a solar system in which the controls are working correctly. This is a requirement for an efficient system but one that is not often experienced. A unique feature of the Page Jackson system is the use of the dual storage tanks. The collector loop draws from the warm storage tank and delivers to the hot storage tank. The space heating and cooling loop draws from the hot tank and returns to the warm tank. The result is that the hottest water is always available to meet the demand. A consequence of the tank design is very little stratification of water in the storage tanks.

Location of the storage tanks in the flow loops presents at least one problem, however. Water required to meet a space heating or cooling load must come directly from the storage tanks and is returned to the tanks after passing through the air handling units. This presents a problem if the storage tanks are depleted of thermal energy. They must be heated by solar or auxiliary energy in the process of meeting the heating or cooling demand, and are a large load themselves, due to their large volume. Additional plumbing to by-pass the tanks would allow loads to be met much more rapidly by the solar or auxiliary system when the tanks are cold.

Relatively large space heating demands were experienced during the past heating season. Three factors combined to produce this load [12]. First, of course, was the weather. As mentioned previously, the month of February was eleven degrees below the long-term average. This is a large variation from the normal. Second, there was a large amount of infiltration into the school. Apparently air leaked around the doors to such an extent that cloth was stuffed into the holes to reduce the cold drafts. Third, attempts were made to have the space heating system produce beyond its design capacity. Possibly as a result of the first two factors, combined with a lack of instruction, the occupants attempted to maintain temperatures above the design temperatures. Hopefully the last two of these factors can be corrected before the next heating season.

During the complete period covered by this report, the solar system achieved a net space heating energy savings of 582.03 million Btu; the electrical expense required to achieve this was 58.46 million Btu.

A total of 1,778.10 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. At times when the collector array was operating there were 1,540.16 million Btu of incident energy on the array. The system collected 356.61 million Btu, which represents an operational efficiency of 23 percent. A total of 370.85 million Btu was delivered to storage during the complete reporting period, and 349.21 million Btu were removed from storage for support of the space heating load.

The space heating load for the complete reporting period was 1,381.26 million Btu. Solar energy supplied 349.21 million Btu of this load and the remaining 1,032.04 million Btu was supplied by the auxiliary fossil fuel system. Due to energy losses between the boiler and the air handling units, a total of 1,167.86 million Btu of thermal energy was generated in the boiler to satisfy the space heating load of 1,032.04 million Btu. This resulted in a solar fraction of 25 percent and a net fossil fuel savings of 582.03 million Btu.

In general, the Page Jackson School solar energy system performed well below the design level. Investigations are currently underway to determine the cause of the collector failures, and what remedies, if any, can be made.

3. SYSTEM DESCRIPTION

Page Jackson School is an elementary school located in Charles Town, West Virginia. The solar energy system is designed to provide approximately 85 percent of the space heating and 50 percent of the space cooling energy requirements of the school. It has an array of 620 PPG flat-plate collectors, with a gross area of 11,216 square feet, that faces south at an angle of 45 degrees from the horizontal. Water is used as the medium for delivering solar energy from the collector array to storage. Freeze protection is accomplished through a drain-down system. The solar heated water is stored in two interconnected 10,000-gallon storage tanks and is used for space heating and cooling. When the solar energy is insufficient to meet the heating demands, an oil-fired boiler is used to provide auxiliary hot water for heating. In the space cooling mode, the hot water from storage is supplied to an absorption chiller to generate chilled water. A conventional centrifugal chiller is used as backup whenever solar energy is insufficient to meet the space cooling demand. The system, shown schematically in Figure 3-1, has three modes of solar operation.

<u>Mode 1 - Collector-to-Storage</u>: The collector subsystem operates independently of the other subsystems. It is active whenever the solar collector temperature is higher than the temperature in storage (hot water thermal storage). When the hot water thermal storage temperature is equal to, or greater than the collector temperature, solar pump P7 is shut down (pump P8 is a backup pump). An emergency mode of operation to prevent overheating of the collectors is manually activated to allow water to continuously circulate through the collectors.

<u>Mode 2 - Space Heating</u>: This mode is entered when the manual SUMMER-WINTER-AUTOMATIC switch is set to AUTOMATIC and the outside ambient temperature is below 60°F, or when the switch is set to WINTER. Whenever the temperature of the air returning from the air-handling units is below 68°F and the hot water thermal storage temperature is less than 123°F, auxiliary heating is activated. The burner for the boiler is cycled to maintain a water temperature of 160°F. When the hot water thermal storage temperature rises above

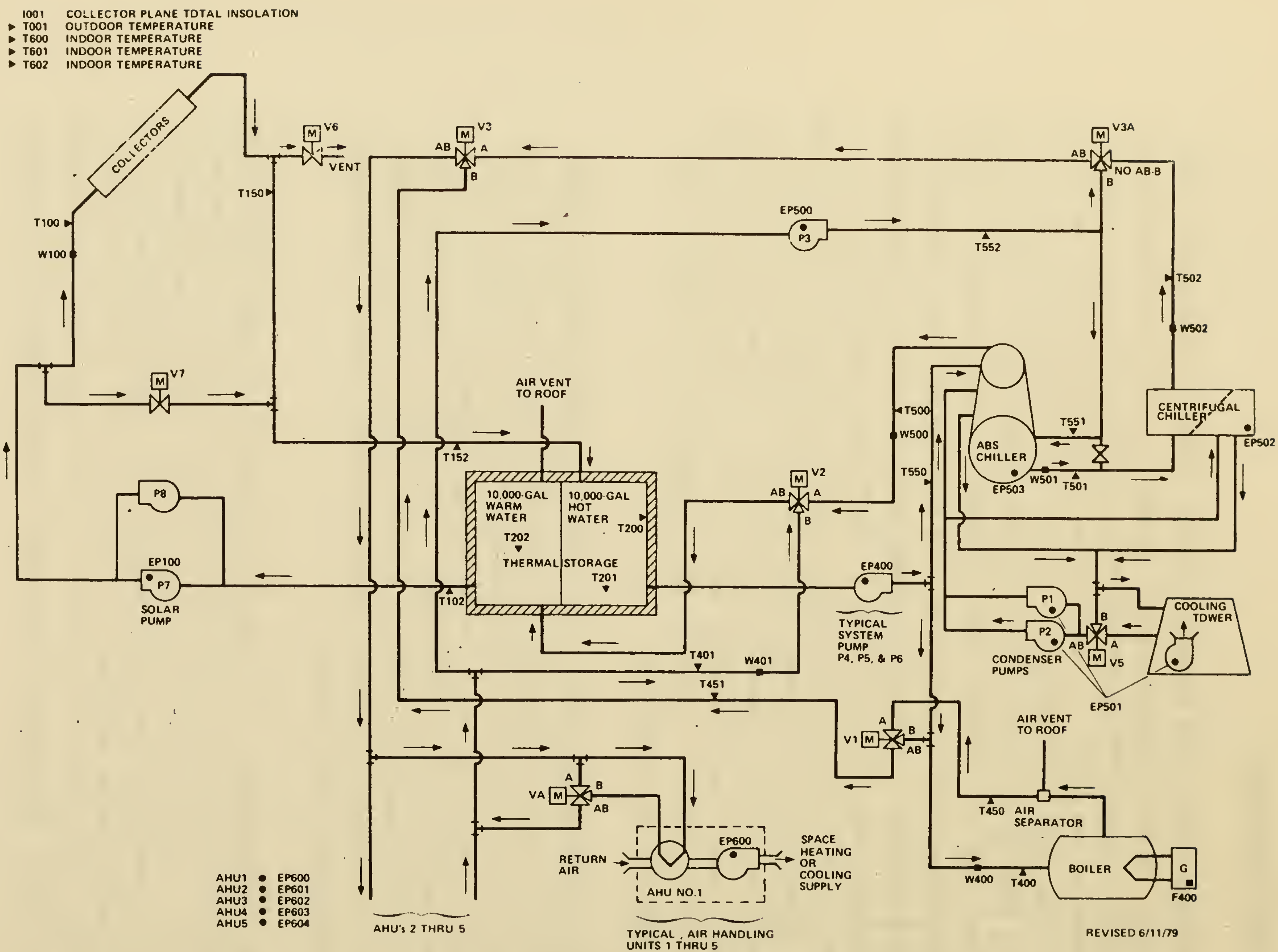

Figure 3-1. PAGE JACKSON SCHOOL SOLAR ENERGY SYSTEM SCHEMATIC

113°F, or the return air temperature rises above 68°F, auxiliary heating is shut off.

Mode 3 - Space Cooling: This mode is entered when the manual SUMMER-WINTER-AUTOMATIC switch is set to AUTOMATIC and the outside ambient temperature is above 68°F, or when the switch is set to SUMMER. There are two modes of space cooling; one utilizes the absorption chiller, the other the backup centrifugal chiller. When the hot water thermal storage temperature rises above 180°F, system pumps P4, P5, and P6 are activated to generate flow through the absorption chiller. As the inlet water temperature to the chiller rises above 180°F, the chilled water temperature out of the absorption chiller will become colder. As the temperature from hot water thermal storage drops below 180°F, the reverse will occur. When the hot water thermal storage temperature drops below 171°F, system pumps will stop, and the absorption chiller will no longer be used for space cooling. If there is a demand for space cooling and the storage temperature is below 171°F, the backup centrifugal chiller is used to satisfy the demand.

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Page Jackson School solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Page Jackson School site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, November 1978 through March 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

5. PERFORMANCE ASSESSMENT

The performance of the Page Jackson School solar energy system has been evaluated for the November 1978 through March 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

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*f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

5.1. Weather Conditions

Average values of the daily incident solar energy in the plane of the collector array and the average outdoor temperature measured at the Page Jackson School site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days are summed monthly.

During the five-month period from November 1978 through March 1979, a daily average of 1,071 Btu/ft^2 of incident solar energy was measured in the plane of the collector array. This was almost identical to the long-term daily average of 1,075 Btu/ft^2. The measured average ambient temperature of the period was 36°F, which was one degree below the long-term average of 37°F.

TABLE 5.1-1

WEATHER CONDITIONS

Month	Daily Incident Solar Energy Per Unit Area (45° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree-Days		Cooling Degree-Days	
	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Nov 78	864	1,068	45	45	602	609	0	0
Dec 78	1,050	836	37	34	872	961	0	0
Jan 79	801	963	29	32	1,123	1,020	0	0
Feb 79	1,158	1,170	23	34	1,170	874	0	0
Mar 79	1,481	1,338	46	42	601	719	5	0
Total	--	--	--	--	4,368	4,183	5	0
Average	1,071	1,075	36	37	874	837	1	0

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined to be the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution.

The thermal performance of the Page Jackson School solar energy system is presented in Table 5.2-1 and Table 5.2-2. This performance assessment is based on the five month period from November 1978 to March 1979.

During the five month reporting period, a total of 356.61 million Btu of solar energy was collected, and the total system load was 1,381.25 million Btu. The measured amount of solar energy delivered to the space heating load was 349.21 million Btu, which was 54 percent less than the expected value. The measured system solar fraction of 25 percent was less than the expected value of 55 percent. These variations were primarily due to the unusual weather and solar collector malfunctions during the reporting period.

The solar energy system COP (defined as the total solar energy delivered to the load divided by the total solar energy system operating energy) was 29.91 for the five month period. The collector array subsystem COP and the space heating subsystem solar COP for the total period were 64.88 and 63.03, respectively. These values again relate the amount of solar energy associated with a particular subsystem to the amount of electrical energy required to operate the solar portion of that subsystem. As such, the COP serves as an indicator of both how well the system was designed and how well it operated. At the Page Jackson School site, the solar energy supplied to the total load for this season is the same as the solar energy supplied to the space heating load, and this is the reason that the overall system COP appears low with respect to the space heating COP. The operating energy required for the

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Nov 78	59.27	185.45	118.6	57.04	53	31
Dec 78	73.72	270.16	160.4	70.99	54	26
Jan 79	51.84	381.83	120.0	51.81	31	14
Feb 79	49.27	362.02	167.6	49.75	41	14
Mar 79	122.51	181.80	186.7	119.62	94	66
Total	356.61	1,381.26	753.3	349.21	---	--
Average	71.32	276.25	150.7	69.84	55	25

TABLE 5.2-2

SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP	Space Cooling Subsystem Solar COP
Nov 78	26.91	55.92	53.81	*
Dec 78	27.62	57.15	55.03	
Jan 79	27.27	57.57	54.54	
Feb 79	32.73	64.83	65.46	
Mar 79	40.41	82.78	80.82	
Total Period	31.55	64.88	63.03	

* The space cooling subsystem was not in use during this period.

solar energy system has been divided equally between the collector array and the space heating subsystem for each month.

It is interesting to note the strong influence that the local weather conditions had on the measured solar fraction. In January 1979, the measured insolation was 17 percent below normal, and the ambient temperature was three degrees below normal. The measured solar fraction was a relatively low 14 percent. In February, the measured insolation increased to one percent below the normal, but the ambient temperature dropped to eleven degrees below normal. The solar fraction was again 14 percent. In March, the measured insolation and ambient temperature both rose to values 10 percent above the normal for the month, and resulted in the measured solar fraction increasing to 66 percent. These observations serve to reinforce the statement in the Performance Assessment section concerning the impact of prevailing weather conditions on the performance of a solar energy system.

5.3 Subsystem Performance

The Page Jackson School solar energy installation may be divided into four subsystems:

1) Collector array
2) Storage
3) Space heating
4) Space cooling.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the four subsystems for the period November 1978 through March 1979.

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i \tag{1}$$

where: η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy (SECA)

Q_i = Incident Solar Energy (SEA).

The gross collector array area is 1,932 square feet. The measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s/\left(Q_{oi} \times \frac{A_p}{A_a}\right) \tag{2}$$

where: Q_s = Collected solar energy (SECA)

Q_{oi} = Operational Incident Energy (SEOP)

Q_p = Gross Collector Area (product of the number of collectors and the total envelope area of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware (GCAA).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Collector array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5.3.1-1.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

The Page Jackson School collector array consists of 620 P.P.G. model A529 double glazed, selective coated flat plate liquid collectors. Additional insulation was added to the backs of these collectors prior to installation to reduce losses to the environment.

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Nov 78	285.19	59.27	0.21	261.70	0.23
Dec 78	358.09	73.72	0.21	335.70	0.22
Jan 79	273.17	51.84	0.19	237.76	0.21
Feb 79	356.78	49.27	0.14	244.36	0.20
Mar 79	504.87	122.51	0.24	460.64	0.27
Total	1,778.10	356.61	--	1,540.16	--
Average	355.62	71.32	0.20	308.03	0.23

Table 5.3.1-2 presents a comparison of the actual performance of the collector array for the month of March to the performance prediction based on the linear instantaneous efficiency curve derived from single panel test data. Figure 5.3.1-1 presents a histogram of collector operating points for March. The month of March was chosen as the example month because the collection array was operational during all but three days. These days experienced very low insolation. It was also felt that the more recent data would be more effective in evaluating the current status of the collector array.

Actual array performance during the month was consistently below the predicted single panel performance. This has been the case during each month of analysis. During March, the array averaged 48 percent below the single panel performance. This difference is extremely large, indicating poor panel performance, but also is the smallest difference seen since analysis began in November.

Additional comparison of collector performance is shown in Figure 5.3.1-2. Straight line efficiency curves as observed for each month from October 1978 through April 1979 are shown, with the single panel design curve as obtained from the manufacturer. October 1978 and April 1979 collector data was available for inclusion into this report, however the remaining subsystem data is not available. The solid portions of the monthly curves indicate the regions in which the collectors were operated for at least 20 percent of the time. The dashed extensions are extrapolations indicating operation for less than 20 percent of the time. February was extremely cold, resulting in efficiencies below the remaining months, and significant variance in the measured data. It was felt that the February collector performance was not typical and hence it is not shown as a solid line. The actual collector performance should fall below the design, or single panel performance due to array losses and non-ideal ambient conditions, but the difference in this case is excessive indicating some collector malfunction. It is important that the monthly curves do not indicate any continuous degradation of the collector array, they appear to be no worse in April than they were in October.

TABLE 5.3.1-2.

ENERGY GAIN COMPARISON
MARCH

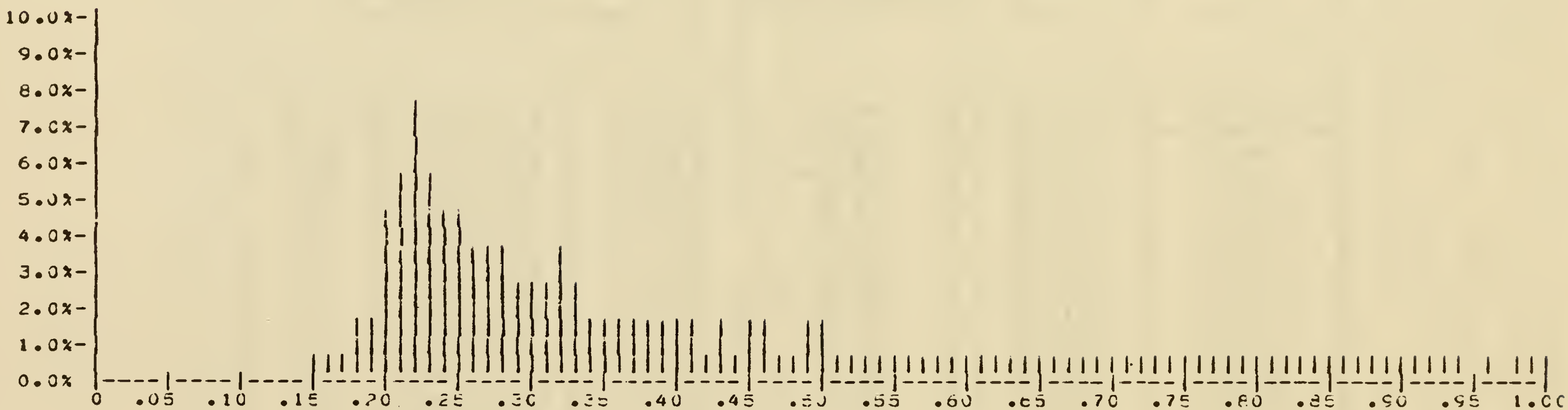
SITE: PAGE JACKSON — CHARLES TOWN, WV

		ERROR			
		FIELD DERIVED			LAB
DAY	ACTUAL	MONTH	LONG TERM	2ND ORDER	PANEL
1	1.643E+06	0.178	0.228	0.721	-0.375
2	5.303E+06	0.003	0.074	0.108	-0.463
3	2.747E+06	-0.088	-0.041	0.062	-0.515
4	0.000E+00	0.000	0.000	0.000	0.000
5	0.000E+00	0.000	0.000	0.000	0.000
6	0.000E+00	0.000	0.000	0.000	0.000
7	6.019E+06	0.142	0.227	0.269	-0.388
8	5.080E+06	0.092	0.172	0.207	-0.415
9	5.608E+06	0.043	0.127	0.158	-0.440
10	1.035E+05	0.019	-0.024	139.377	-0.474
11	3.713E+06	-0.068	-0.018	0.130	-0.504
12	6.906E+06	-0.006	0.070	0.087	-0.467
13	5.889E+06	-0.041	0.033	0.046	-0.486
14	2.215E+06	-0.062	0.007	0.079	-0.497
15	6.854E+06	-0.044	0.026	0.053	-0.488
16	7.016E+06	0.014	0.090	0.110	-0.457
17	6.852E+06	-0.010	0.067	0.094	-0.469
18	4.796E+06	-0.069	0.008	0.030	-0.500
19	6.805E+06	-0.017	0.058	0.086	-0.473
20	7.101E+06	0.028	0.109	0.133	-0.449
21	6.714E+06	-0.027	0.049	0.072	-0.478
22	6.345E+06	-0.032	0.043	0.066	-0.481
23	3.606E+06	-0.186	-0.135	-0.115	-0.565
24	1.992E+05	-0.360	-0.329	-0.246	-0.660
25	1.424E+06	0.112	0.117	1.053	-0.417
26	9.261E+05	-0.314	-0.294	-0.103	-0.637
27	3.710E+06	-0.077	-0.019	0.037	-0.507
28	6.392E+06	-0.045	0.027	0.050	-0.488
29	5.192E+06	-0.098	-0.024	0.002	-0.516
30	2.741E+06	-0.123	-0.065	0.012	-0.531
31	7.319E+04	-0.453	-0.521	-6.674	-0.726
	1.219E+08	-0.025	0.046	0.094	-0.478

CURVE	COEFFICIENTS			
	A0 (BETA)	A1 (FULL)	A2 (*)	R**2
PANEL	0.750	-0.690	N.A.	N.A.
MONTH	0.407	-0.387	N.A.	0.294
LT1ST	0.363	-0.306	N.A.	0.102
LT2ND	0.329	-0.015	-0.541	N.A.

PAGE JACKSON CHARLES TOWN, WV

COLLECTOR TYPE: FPC COLLECTOR MODEL: A414



OPERATING POINT HISTOGRAM - MARCH

FLUID PROPERTIES - MARCH

	WATER			
	COEFFICIENTS			
PROPERTY	A0	A1	A2	A3
SPECIFIC HEAT	1.011E+00	-2.348E-04	1.037E-06	
DENSITY	8.346E+00	4.129E-04	-9.961E-06	

ARRAY FLOW RATE 202.52 GPM

PANEL FLOW RATE 0.32 GPM

AVERAGE TEMPERATURE GAIN 6.97 DEGR FAHRENHEIT

LONG TERM CURVE FIT VALID FROM 0.165 TO 0.394 .

Figure 5.3.1-1. COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES

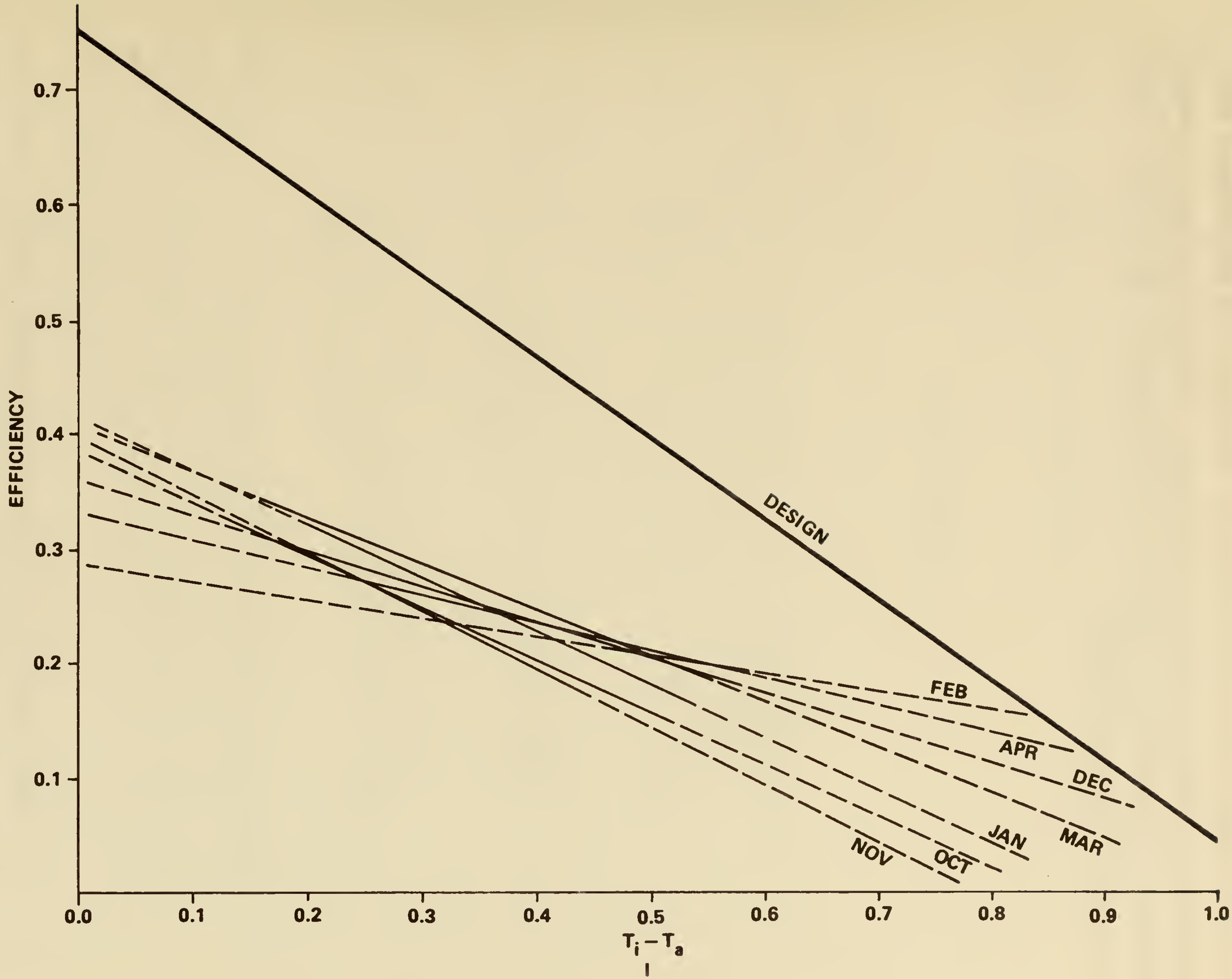


Figure 5.3.1-2. PAGE JACKSON SCHOOL COLLECTOR PERFORMANCE OCTOBER 1978 THROUGH APRIL 1979

The average monthly operational collector efficiency for the November 1978 through March 1979 time period was 23 percent. The month of March averaged 27 percent, indicating that higher collector array efficiencies may be experienced during the coming months.

5.3.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \qquad (5)$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH).

Q_{so} = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium (STEO).

Q_{si} = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI).

Evaluation of the system storage performance under actual transient system operation and weather conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the storage subsystem design can be derived empirically as a function of storage average temperature (average storage temperature for the reporting period) and the ambient temperature in the vicinity of the storage tank.

An effective storage heat transfer coefficient (C) for the storage subsystem can be defined as follows:

$$C = (Q_{si}-Q_{so}-\Delta Q_s)/[(\overline{T}_s - \overline{T}_a) \times t] \ \frac{Btu}{Hr\text{-}°F} \qquad (6)$$

where:

C = effective storage heat transfer coefficient

Q_{si} = energy to storage (STEI)

Q_{so} = energy from storage (STEO)

ΔQ_s = change in stored energy (STECH)

$\overline{T}_s$ = storage average temperature (TS)

$\overline{T}_a$ = average ambient temperature in the vicinity of storage (TE)

t = number of hours in the month (HM).

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in this report period and included, along with Storage Average Temperature, in Table 5.3.2-1.

Examination of the values for the effective storage heat transfer coefficient show a significant amount of scatter for the four month period from November 1978 through March 1979. The mean for these months was 93.01 Btu/Hr-°F, but the standard deviation was 150.04 Btu/Hr-°F. The exact reason for this scatter is not known, but there are two factors that must be considered. First, it can be seen that the storage subsystem is operating at a fairly low temperature. This, of course,

TABLE 5.3.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Storage Heat Loss Coefficient (Btu/Hr°-F)
Nov 78	57.04	57.04	-1.86	0.97	114	46.97
Dec 78	70.99	70.99	-0.58	0.99	111	13.68
Jan 79	51.81	51.81	0.09	1.00	106	2.18
Feb 79	67.24	49.75	5.54	0.82	97	359.25
Mar 79	123.77	119.62	2.34	0.98	119	42.97
Total	370.85	349.21	5.53	--	--	--
Average	74.17	69.84	1.11	0.96	109	93.01

resulted from the large space heating loads that were experienced during this period combined with the poor collector array performance. A low storage temperature reduces the value of the denominator in equation (4) and causes the calculation to become very sensitive to the values used for storage and ambient temperature. Secondly, two separate storage tanks are used at this site. They are being treated as one tank and the average value of the two is being used for the storage temperature. If the temperature readings from these three sensors do not truly represent the overall average temperature of the water in the two 10,000 gallon tanks, due to problems such as thermal stratification, unrepresentative sensor location, sensor inaccuracy, or less than full tanks, significant variation may result because of the sensitivity to temperature difference mentioned previously. Third, the tanks are located in an equipment room which is not instrumented to determine the ambient temperature around the tanks. It was felt that the room would be warmer than the outside temperature due to the heat producing equipment in nearby areas, but cooler than the temperature in the classroom area. For this reason, a room temperature was assumed to be the average of the outside ambient, and the classroom temperatures.

An additional analysis of storage performance was performed by observing storage performance during a period when no thermal energy was either added to storage by the collectors or boiler or removed to support system loads. Two consecutive days were found during which there was no flow to or from the tanks. Indicated temperatures in the tanks are shown in Figure 5.3.2-1. Sensor T202 is located approximately in the center of warm water storage area, sensor T200 is in the upper portion of the hot water tank and sensor T201 is in the lower portion of the hot water tank. A visual comparison of T200 and T201 shows the effect of thermal stagnation when no circulation is experienced.

This spatial temperature differential causes a problem in estimating the overall energy content of the tanks. Figure 5.3.2-1 indicates that both tanks are at approximately the same temperature. To determine that temperature, it was assumed that sensor T200 represents the temperature of

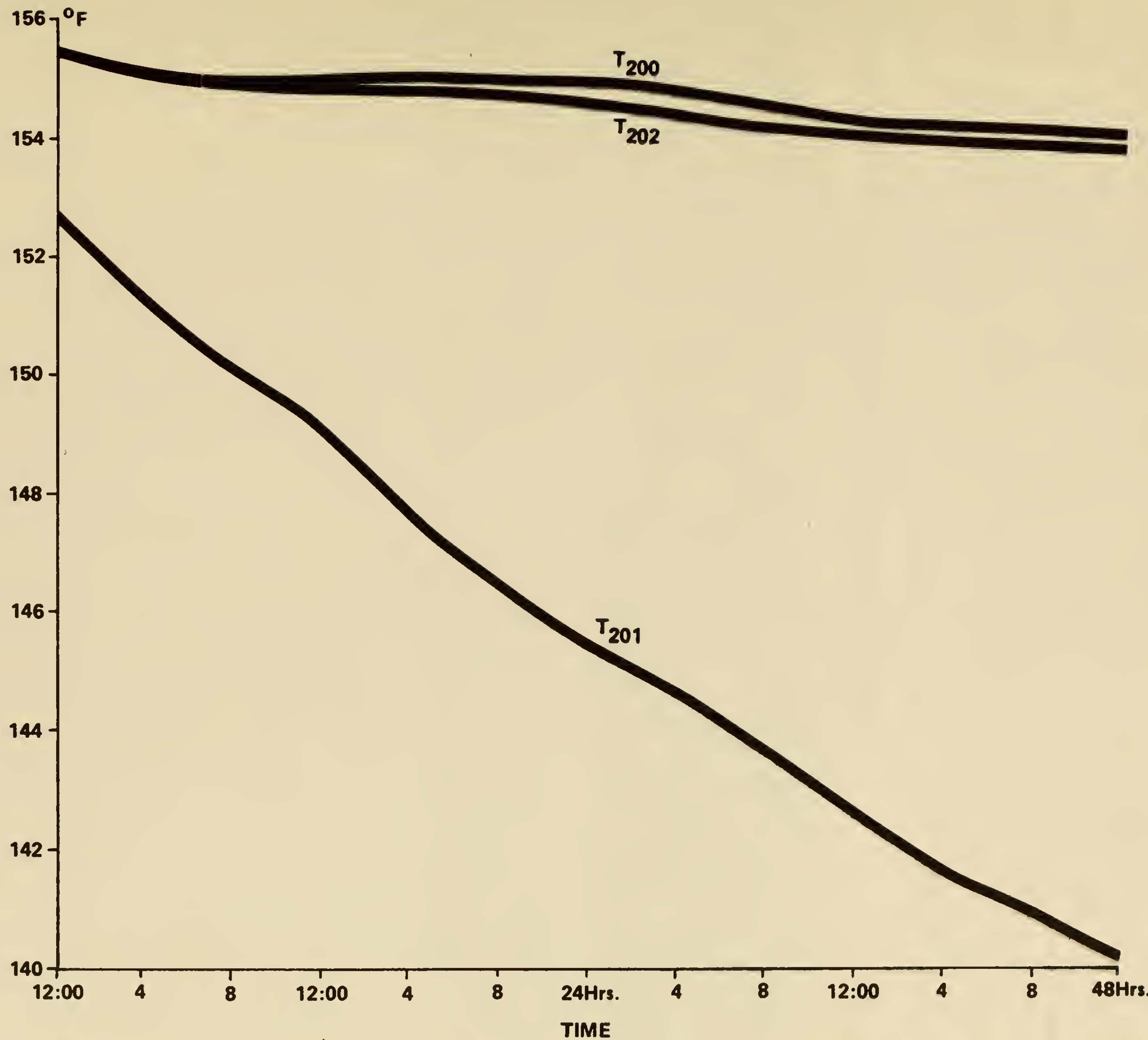


Figure 5.3.2-1. TEMPERATURE PROFILES OF THE PAGE JACKSON STORAGE TANKS

the upper three-fourths of the tank and T201 represents the lower one-fourth of the tank. It was felt that this was a legitimate assumption, based on the location of the sensors in the tanks and thermal stratification measurements made on other storage tanks. As before, the ambient temperature in the vicinity of storage was taken as the average of the outside ambient temperature and the temperature of the conditioned classroom space. Determining the change in stored energy from the temperature sensors, and with no energy to or from storage, the effective storage heat transfer coefficient was calculated to be 146.87 Btu/Hr-°F for the two day period.

Comparing this value with the average heat loss coefficient of 93.01 Btu/Hr-°F for the five-month period from Table 5.3.2-1 it can be assumed that these methods may be too approximate for this system. Some relatively gross approximations were made for determining the temperature external to the tanks and for the actual energy content of the tanks. The energy loss from the tanks should be significantly less than this value knowing that the tanks are insulated with six inches of urethane foam.

5.3.3 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the Page Jackson School space heating subsystem is presented in Table 5.3.3-1. For the five-month period from November 1978 through March 1979, the solar energy system supplied a total of 349.21 million Btu to the space heating load. The total heating load for this period was 1,381.26 million Btu, and the average solar fraction was therefore 25 percent. As mentioned earlier, the small solar fractions experienced during January and February 1979 were a result of the severe winter environment. The dramatic increase in solar fraction during the month of March is a result of a significant increase in incident solar energy (42 percent larger than the average for the five month period) combined with the smallest heating load of the period.

TABLE 5.3.3-1

HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million. Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Nov 78	185.45	57.04	167.91	270.54	31
Dec 78	270.16	70.99	226.68	294.97	26
Jan 79	381.83	51.81	340.08	566.80	14
Feb 79	362.02	49.75	354.21	590.35	14
Mar 79	181.80	119.62	78.98	131.64	66
Total	1,381.26	349.21	1,167.86	1,854.30	--
Average	276.25	69.84	233.57	370.86	25

5.4 Operating Energy

Operating energy for the Page Jackson School solar energy system is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system during this time period consists of energy collection and storage subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. For this five month reporting period, the total operating energy for each month was divided evenly between the ECSS subsystem and the space heating subsystem. Measured monthly values for subsystem operating energy are presented in Table 5.4-1.

Total system operating energy for the Page Jackson School is that electrical energy required to operate the circulation pump in the collector loop. This is shown as EP101 in Figure 3-1. Although additional electrical energy is required to operate the other pumps in the system they are not included as solar operating energy. These devices would be used in a conventional system and should not be charged against the solar system.

For the overall period covered by this report, a total of 11.07 million Btu of operating energy was consumed. During the same time a total of 349.21 million Btu of solar energy was supplied to the space heating load. Therefore, for every one million Btu of solar energy delivered to the load, 0.03 million Btu (or 9.29 kwh) of electrical operating energy was expended.

TABLE 5.4.1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Space Cooling Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Nov 78	1.06	1.06	*	2.12
Dec 78	1.29	1.29		2.57
Jan 79	0.95	0.95		1.90
Feb 79	0.76	0.76		1.52
Mar 79	1.48	1.48		2.96
Total	5.54	5.54		11.07
Average	1.11	1.11		2.21

* The Space Cooling Subsystem was not in use during this period.

5.5 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

The auxiliary source at the Page Jackson School consists of an oil fired boiler which may provide thermal energy directly to the air-handling units for space heating, or to the absorbtion chiller to be used for space cooling. The efficiency of this boiler in converting the energy content of the oil into thermal energy in the water averaged 63 percent over the five month period.

Electrical energy savings for November 1978 through March 1979 are presented in Table 5.5-1. For this time period, the average gross monthly savings were a negative 9.50 million Btu, indicating an expense. After the total system operating energy was deducted, the average net monthly savings were -11.69 million Btu, or -3,426 kwh. For the overall time period covered by this report the total net electrical savings were -58.46 million Btu, or -17,130 kwh. The net fossil savings, however, were positive, indicating a conservation of energy. The average monthly value was 116.41 million Btu, and for the overall time period covered by this report, the total net fossil savings were 582.03 million Btu.

TABLE 5.5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)		Fossil Energy Savings (Million Btu)		Solar Operating Energy (Million Btu)	Net Savings		
						Electrical		Fossil
	Space Heating	Space Cooling	Space Heating	Space Cooling		Million Btu	kwh	Million Btu
Nov 78	-9.46	*	95.07	*	2.13	-11.59	-3,394	95.07
Dec 78	-9.80		118.33		2.57	-12.37	-3,624	118.33
Jan 79	-9.81		86.35		1.80	-11.61	-3,402	86.35
Feb 79	-8.78		82.92		1.52	-10.30	-3,018	82.92
Mar 79	-9.64		199.36		2.96	-12.60	-3,692	199.36
Total	-47.49		582.03		9.49	-58.47	-17,130	582.03
Average	-9.50		116.41		1.90	-11.69	-3,426	116.41

* The space cooling subsystem was not in use during this period.

6. REFERENCES

1. U.S. Department of Energy, National Solar Data Network, Prepared under Contract Number EG-77-C-01-4049, by IBM Corporation, December, 1977.

2. J. T. Smok, V. S. Sohoni, J. M. Nash, "Processing of Instrumented Data for the National Solar Heating and Cooling Demonstration Program," Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April, 1978.

3. E. Streed, et. al., Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, August, 1976.

4. Mears, J. C. Reference Monthly Environmental Data for Systems in the National Solar Data Network. Department of Energy report SOLAR/0019-79/36. Washington, D.C., 1979.

5. ASHRAE Standard 93-77, Methods of Testing to Determine the Thermal Performance of Solar Collectors, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

6. ASHRAE Standard 94-77, Methods of Testing Thermal Storage Devices Based on Thermal Performance, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

7.* Monthly Performance Report, Page Jackson School, SOLAR/2036-78/11, Department of Energy, Washington (November 1978).

8.* Monthly Performance Report, Page Jackson School, SOLAR/2036-78/12, Department of Energy, Washington (December 1978).

9.* Monthly Performance Report, Page Jackson School, SOLAR/2036-79/01, Department of Energy, Washington (January 1979).

10.* Monthly Performance Report, Page Jackson School, SOLAR/2036-79/02, Department of Energy, Washington (February 1979).

11.* Monthly Performance Report, Page Jackson School, SOLAR/2036-79/03, Department of Energy, Washington (March 1979).

12. Personal Communication, Mr. Martin Spaulding, June, 1979.

*Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the distribution loop and other components in the system design which are necessary to mechanize the collector and energy distribution and conversion equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

SPACE COOLING SUBSYSTEM

The space cooling subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space cooling load and in controlling the temperature of the conditioned space.

- SPACE COOLING LOAD (CL) is the total energy, including sensible and latent, removed from the air in the space-cooling area of the building.

- SOLAR FRACTION OF LOAD (CSFR) is the percentage of the demand which is supported by solar energy.

- SOLAR ENERGY USED (CSE) is the amount of solar energy supplied to the space-cooling subsystem.

- OPERATING ENERGY (COPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (CAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (CAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (CSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE PAGE JACKSON SCHOOL

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \bar{C}_p\ \Delta T$$

where $\bar{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY (BTU)

$$SEA = (1/60) \times \Sigma\ [I001 \times AREA] \times \Delta\tau$$

INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD\ (T_2, T_1) = \int_{T_1}^{T_2} C_p(T)dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

COLLECTED SOLAR ENERGY (BTU)

$$SECA = \Sigma\ [M100 \times HWD(T150, T100)] \times \Delta\tau$$

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT.)

$$SEC = \Sigma\ [M100 \times HWD(T150, T100)/AREA] \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

TOTAL SYSTEM OPERATING ENERGY (BTU)

SYSOPE = ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

AVERAGE BUILDING TEMPERATURE (DEGREES F)

$$TB = (1/60) \times \Sigma\ \underline{(T600 + T601 + T602)} \times \Delta\tau$$

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY (BTU)

CSOPE = $56.8833 \times \Sigma\ EP100 \times \Delta\tau$

LOAD SUBSYSTEM SUMMARY:

HEATING FOSSIL SAVINGS (BTU)

HSVF = SOLAR ENERGY TO HEATING/0.6.

HEATING ELECTRICAL SAVINGS (BTU)

HSVE = $-56.8833 \times \Sigma\ EP400 \times \Delta\tau$

COOLING ELECTRICAL SAVINGS (BTU)

CSVE = (COOLING LOAD/COOLING COP) $-56.8833 \times \Sigma\ EP400 \times \Delta\tau$

$-0.7 \times \Sigma\ EP502 \times \Delta\tau$

TOTAL FOSSIL SAVINGS = HSVF

TOTAL ELECTRICAL SAVINGS (BTU)

TSVE = HSVE + CSVE - CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = AUXILIARY THERMAL ENERGY + OPERATING ENERGY + SOLAR ENERGY COLLECTED

LOAD SUBSYSTEM SUMMARY (BTU):

HEATING LOAD

HL = $\Sigma\ [M401 \times HWD\ (T451, T401)] \times \Delta\tau$

COOLING LOAD

CL = $\Sigma\ [M502 \times HWD\ (T552, T502)] \times \Delta\tau$

SYSTEM LOAD (BTU)

SYSL = HL + CL

HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HEATING SOLAR ENERGY/HEATING LOAD)

COOLING SOLAR FRACTION (PERCENT)

CSFR = 100 x (1.- COOLING AUXILIARY THERMAL ENERGY/COOLING LOAD)

SOLAR ENERGY USED:

HEATING SOLAR ENERGY (BTU)

HSE = HL - AUXILIARY HEATING - AUXILIARY ENERGY TO STORAGE

COOLING SOLAR ENERGY (BTU)

$CSE = \Sigma\ [M500 \times HWD\ (T550,\ T500)] \times \Delta\tau$

TOTAL SOLAR ENERGY TO LOADS (BTU)

SEL = HSE + CSE

OPERATIONAL INCIDENT ENERGY (BTU)

$SEOP = (1/60)\ \Sigma\ [I001 \times AREA] \times \Delta\tau$

WHENEVER COLLECTOR PUMP IS RUNNING

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

DAYTIME AMBIENT TEMP (DEGREES F)

$TDA = (1/360)\ \Sigma\ T001 \times \Delta\tau$

$\pm$ 3 HOURS FROM SOLAR NOON

OPERATING ENERGY (BTU):

HEATING OPERATING ENERGY

$HOPE = 56.8833 \times \Sigma\ (EP400 + EP600 + EP601 + EP602 + EP603 + EP604) \times \Delta\tau$

COOLING OPERATING ENERGY

$COPE = 56.8833 \times \Sigma\ (EP400 + EP600 + EP601 + EP602 + EP603 + EP604 + EP500 + EP501 + EP503) \times \Delta\tau$

TOTAL OPERATING ENERGY

SYSOPE = CSOPE + HOPE + COPE

AUXILIARY THERMAL ENERGY (BTU)

HAT = HEATING AUXILIARY THERMAL ENERGY

CAT = COOLING AUXILIARY THERMAL ENERGY

HEATING AUXILIARY FOSSIL FUEL

HAF = 140,000.0 x F400

AUXILIARY ELECTRICAL ENERGY (BTU)

$CAE = 0.7 \times \Sigma\ EP502 \times \Delta\tau$

TOTAL AUXILIARY THERMAL ENERGY

AXT = CAT + HAT

TOTAL AUXILIARY FOSSIL FUEL (BTU)

AXT = HAF

TOTAL AUXILIARY ELECTRICAL ENERGY (BTU)

AXE = CAE

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: PAGE JCKSN SCH. 46. LOCATION: CHARLES TOWN WV

ANALYST: H. SMITH PDRIVE NO.: 64.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 39.30 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1364.	571.	0.41897	1.685	963.	1020	0	32.
FEB	1826.	815.	0.44628	1.436	1170.	874	0	34.
MAR	2420.	1125.	0.46459	1.190	1338.	719	0	42.
APR	3036.	1460.	0.48095	0.988	1442.	357	0	53.
MAY	3466.	1718.	0.49569	0.865	1486.	131	57	63.
JUN	3640.	1902.	0.52266	0.813	1547.	5	188	71.
JUL	3548.	1818.	0.51237	0.836	1520.	0	319	75.
AUG	3197.	1619.	0.50625	0.933	1511.	0	267	74.
SEP	2639.	1342.	0.50855	1.114	1495.	43	100	67.
OCT	1997.	1003.	0.50207	1.383	1387.	291	9	56.
NOV	1471.	653.	0.44376	1.636	1068.	609	0	45.
DEC	1237.	483.	0.39030	1.731	836.	961	0	34.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.